# Edge plasma modeling for divertor configurations with secondary x-points

**M.V. Umansky**

***Acknowledgments:***

**M.E. Rensink, T.D. Rognlien D.D. Ryutov (LLNL)**

**B. LaBombard, D. Brunner, J.L. Terry, D.G. Whyte (MIT)**

*Presented at BOUT++ Workshop, LLNL, Livermore, CA, Dec 16-18, 2015*

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Security, LLC, Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

LLNL-PRES-643674

# Outline

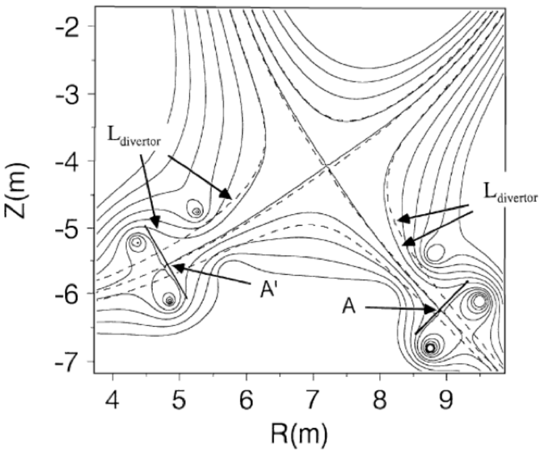
- Divertor configurations with secondary X-points
- Snowflake divertor experiments
- X-Point target divertor
- Topology and grids for edge domain with two x-points
- UEDGE analysis of near-snowflake divertor configurations
- UEDGE analysis of X-point target divertor configuration
- Summary/Conclusions

# Outline

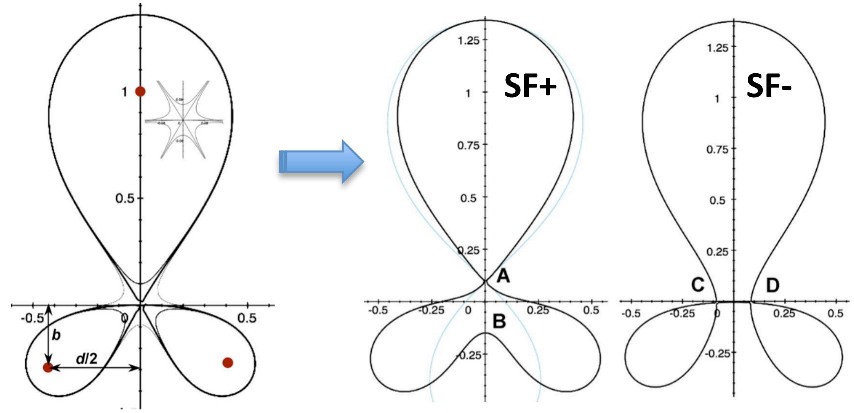
- **Divertor configurations with secondary X-points**
- Snowflake divertor experiments
- X-Point target divertor
- Topology and grids for edge domain with two x-points
- UEDGE analysis of near-snowflake divertor configurations
- UEDGE analysis of X-point target divertor configuration
- Summary/Conclusions

# Configurations with a secondary X-point in divertor considered by many groups in recent years; for example

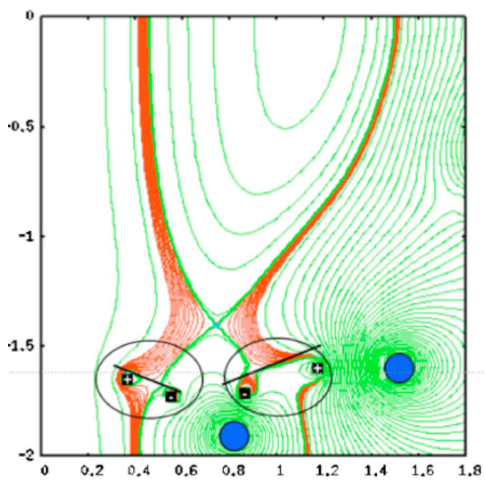
## Cusp divertor [1]



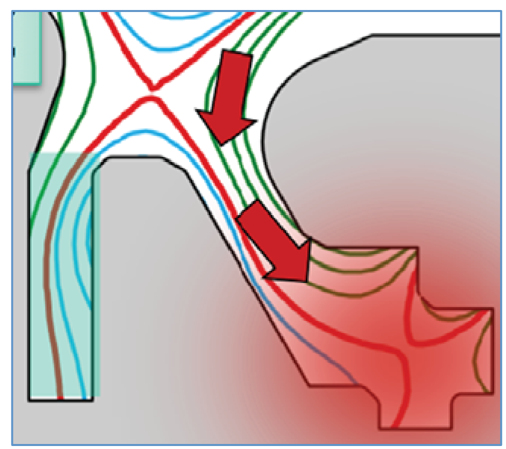

## Snowflake divertor [2]




## X-divertor [3]




## X-point target divertor [4]



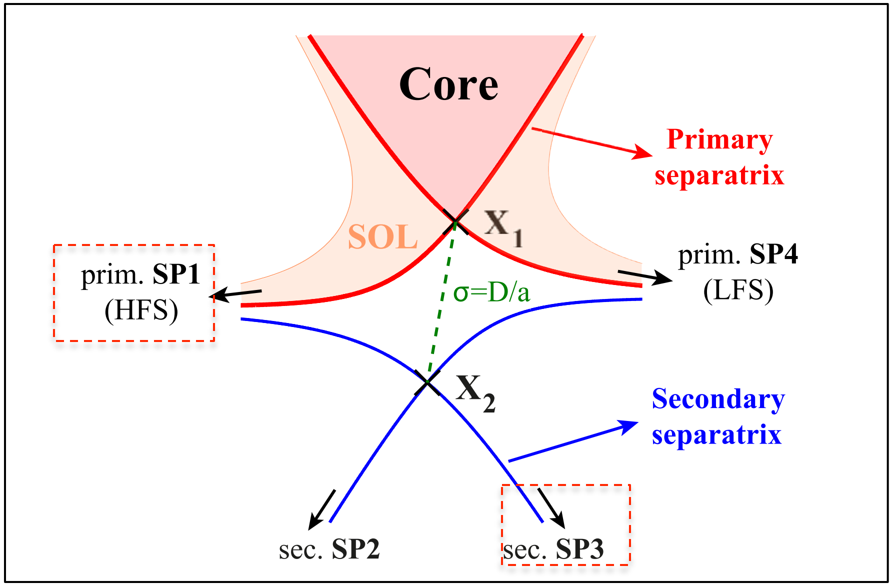
[1] H. Takase, J. Phys. Soc. Japan, 70, 609, 2001.
[2] D.D. Ryutov. Phys. Plasmas, 14, 064502, 2007.
[3] M. Kotschenreuther et al., 2004 IAEA FEC, paper IC/P6-43.
[4] B. LaBombard et al., Nucl. Fusion 55, 053020, 2015.

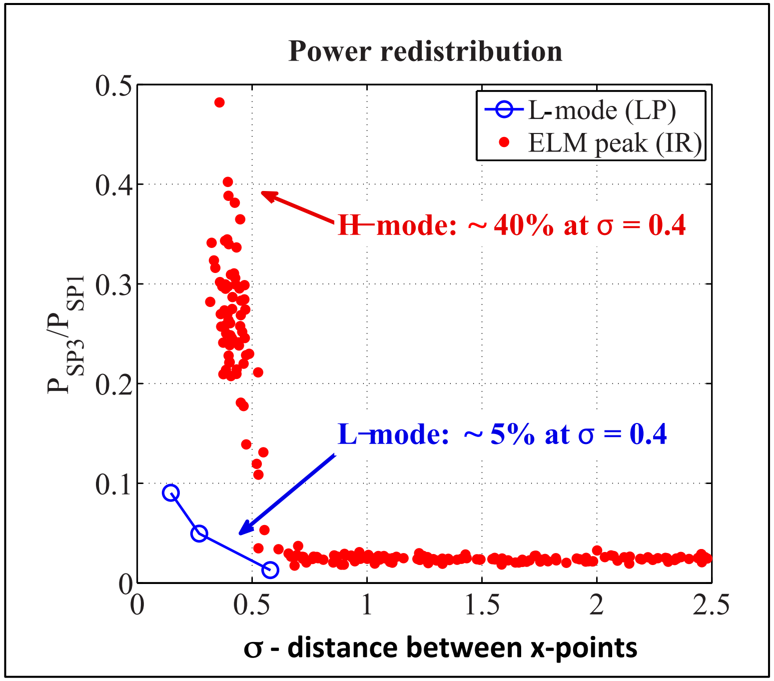
# Outline

- Divertor configurations with secondary X-points
- **Snowflake divertor experiments**
- X-Point target divertor
- Topology and grids for edge domain with two x-points
- UEDGE analysis of near-snowflake divertor configurations
- UEDGE analysis of X-point target divertor configuration
- Summary/Conclusions

# Experiments on TCV tokamak indicate that enhanced transport zone may exist near the null-point

**Figures from Vijvers et al, NF 2014**

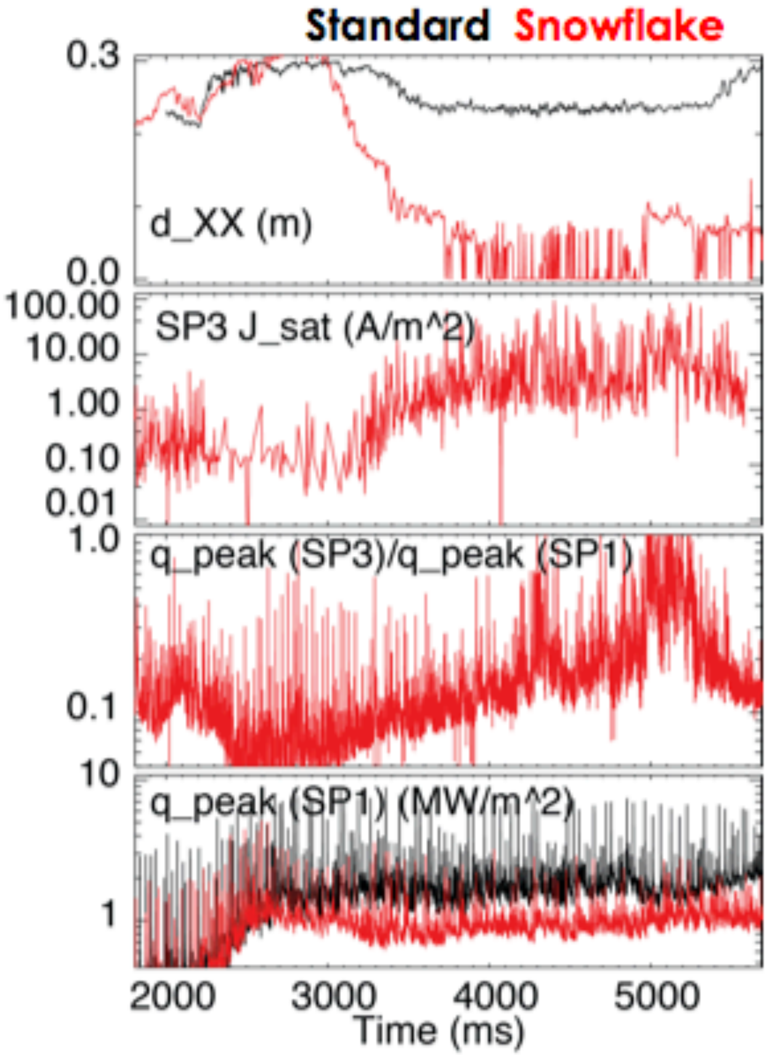


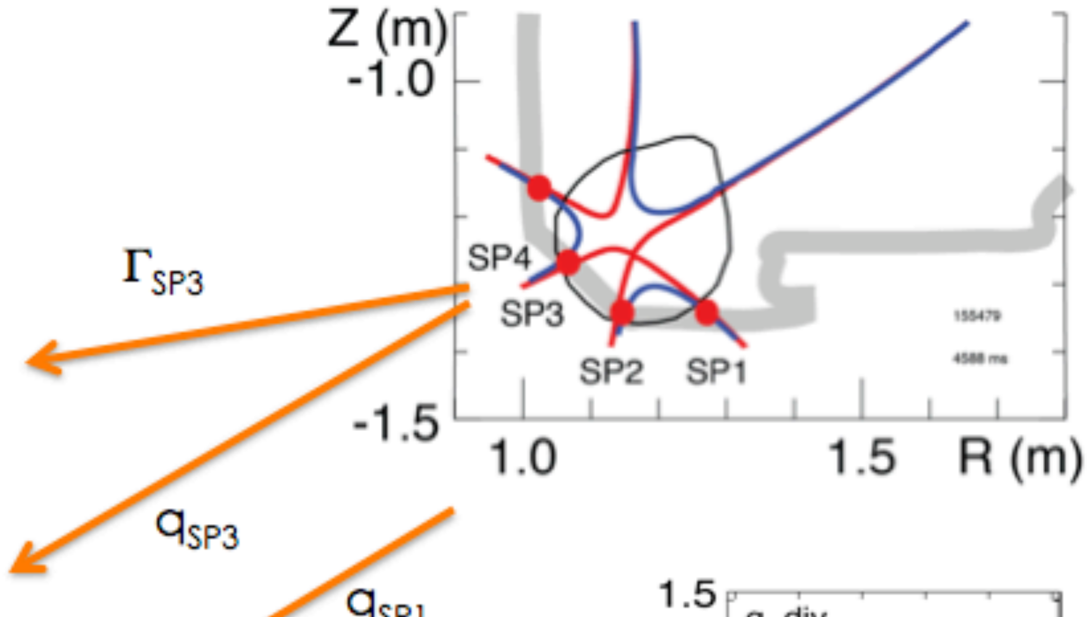




**Large fraction of power flows to secondary strike points**

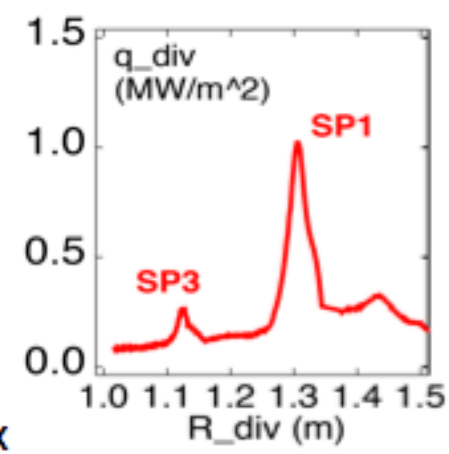
- **when two X-points get closer**
- **more during ELM strike**

# DIII-D: heat and particle fluxes shared among strike points in snowflake divertor (Soukhanovskii – FEC ’14)




- $q_{SP3} / q_{SP1} < 0.5$
- $P_{SP3} / P_{SP1} < 0.3$
- Sharing fraction maximized at low $d_{XX}$



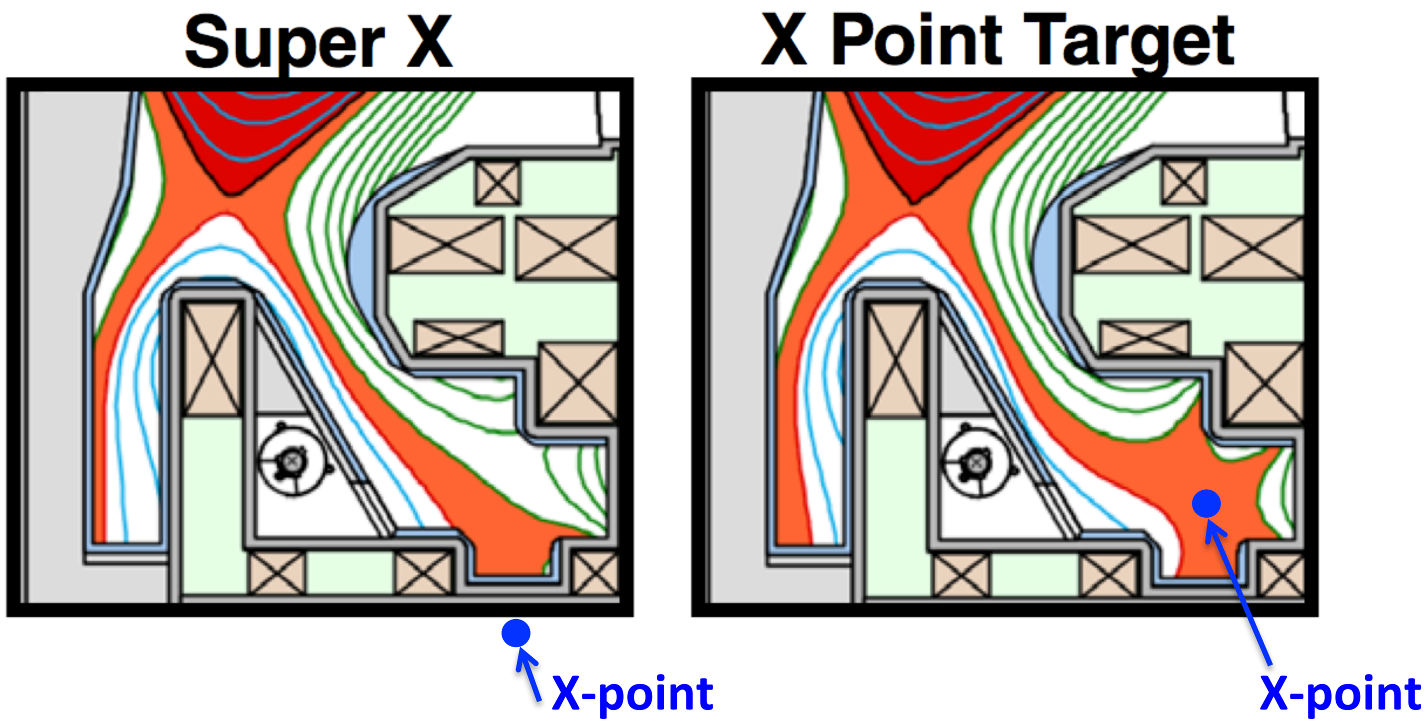


DIII-D NATIONAL FUSION FACILITY

# Outline

- Divertor configurations with secondary X-points
- Snowflake divertor experiments
- **X-Point target divertor**
- Topology and grids for edge domain with two x-points
- UEDGE analysis of near-snowflake divertor configurations
- UEDGE analysis of X-point target divertor configuration
- Summary/Conclusions

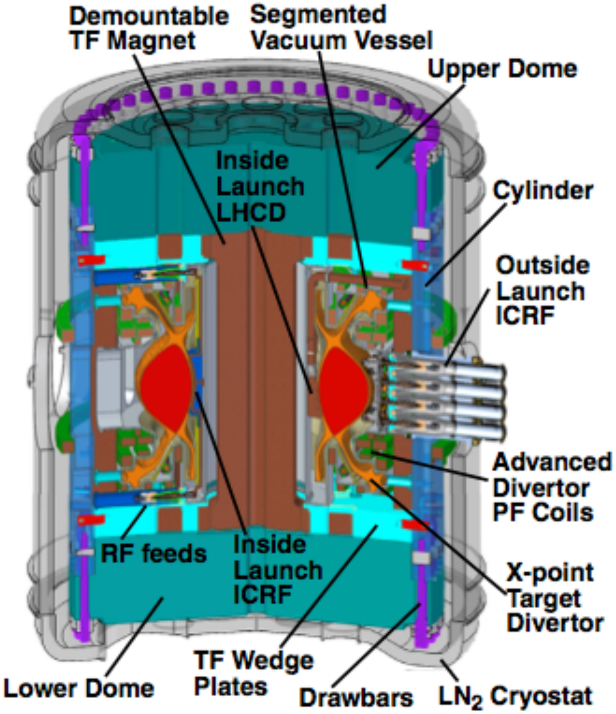
# X-point target divertor is similar to the super-X divertor, but with the second X-point in the plasma volume




- Like Super-X, exploits 1/R geometric reduction of divertor heat flux
- May produce stable 'X-point MARFE' in the divertor chamber
- Used as a part of the ADX tokamak concept

XPTD: LaBombard *et al.* 2013 *Bull. Am. Phys. Soc.* 58 63, and Nucl. Fusion 55, 053020, 2015.
SXD: P. Valanju *et al., Phys. Plasmas* 16, 056110 (2009)

# X-point target divertor study is motivated by the ADX tokamak concept discussed at MIT PSFC




| ADX | |
|---|---|
| Major/Minor Radius | 0.73 / 0.2 m |
| Elongation | 1.7 |
| Magnetic Field | 6.5 Tesla (8 Tesla with power upgrade) |
| Plasma Current | 1.5 MA (2 MA) |
| $P_{AUX}$ | 10 MW ICRF<br>4 MW LHCD<br>Inside Launch |
| Surface Power Density | ~ 1.7 MW/m² |
| $P_{AUX}$ B/R | 125 MW-T/m |
| Advanced Divertor Concepts | Super X<br>X-point target<br>Snowflake<br>X divertor<br>Liquid metal |
| First-wall material | Tungsten, Molybdenum; high temp. options |
| Pulse length at max. field, current | 3s, with 1s flat-top |

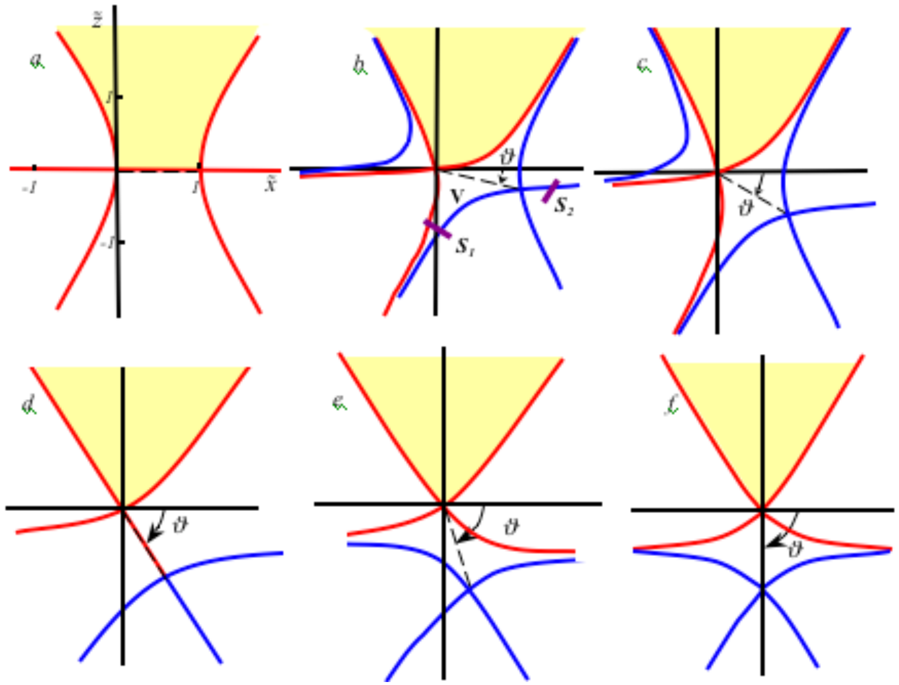
- ADX = Advanced Divertor and RF tokamak eXperiment*
- Designed to address critical gaps on pathway to next-step devices
- Advanced divertors
- Advanced RF actuators
- Reactor-prototypical core plasma conditions

*B. LaBombard et al., Nucl. Fusion 55, 053020, 2015.

# Outline

- Divertor configurations with secondary X-points
- Snowflake divertor experiments
- X-Point target divertor
- **Topology and grids for edge domain with two x-points**
- UEDGE analysis of near-snowflake divertor configurations
- UEDGE analysis of X-point target divertor configuration
- Summary/Conclusions

# Topological classification of configurations with secondary x-point in the divertor



- Derived from local expansion for inexact snowflake
- Applies to any configuration with secondary x-point
- $\theta$ = angle between X-point bisector and horizontal axis
- In addition to shown six cases, there are mirror reflections of cases b,c,d,e

Ryutov et al., PPCF 52 (2010) 105001

# Recent upgrades made in UEDGE include generalization of computational subdomains and mesh generation

$\theta$ = angle between X-point bisector & horizontal axis

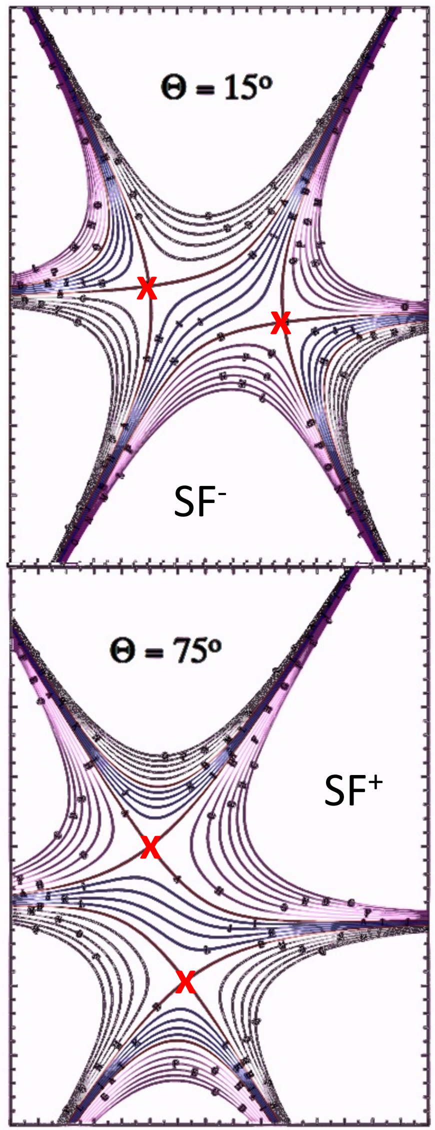
**3 mesh regimes**

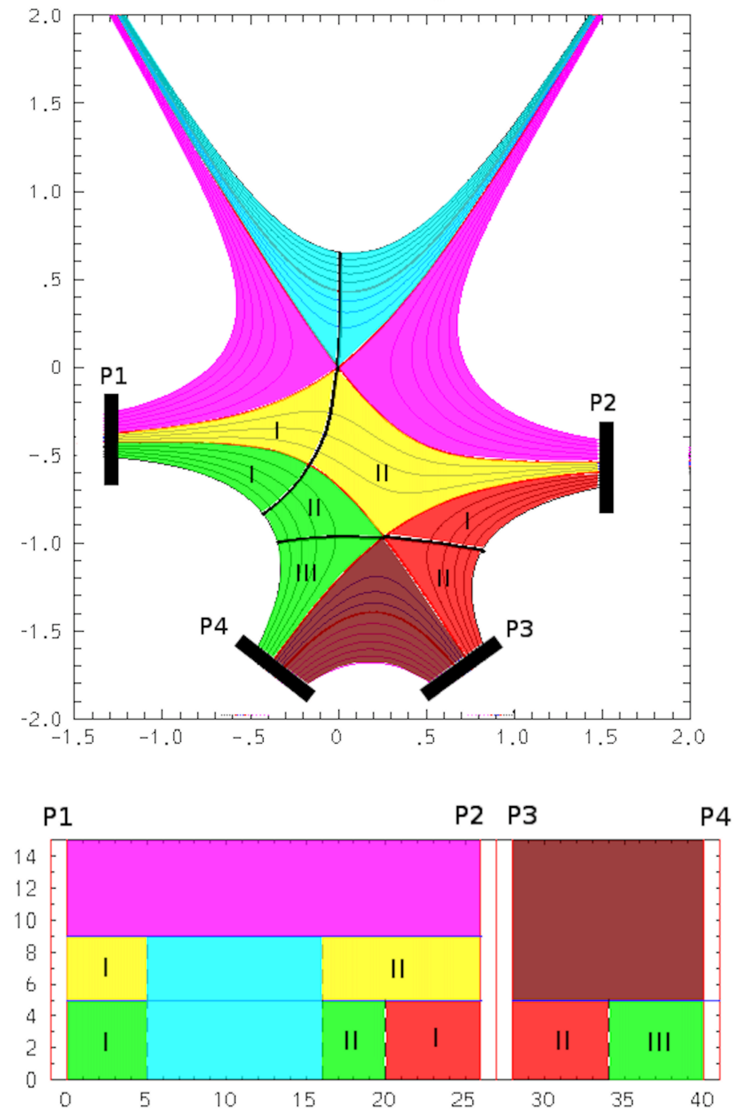
$0 < \theta < 30^o$

$30^o < \theta < 60^o$

$60^o < \theta < 90^o$

Unique indexing rules for each regime completed

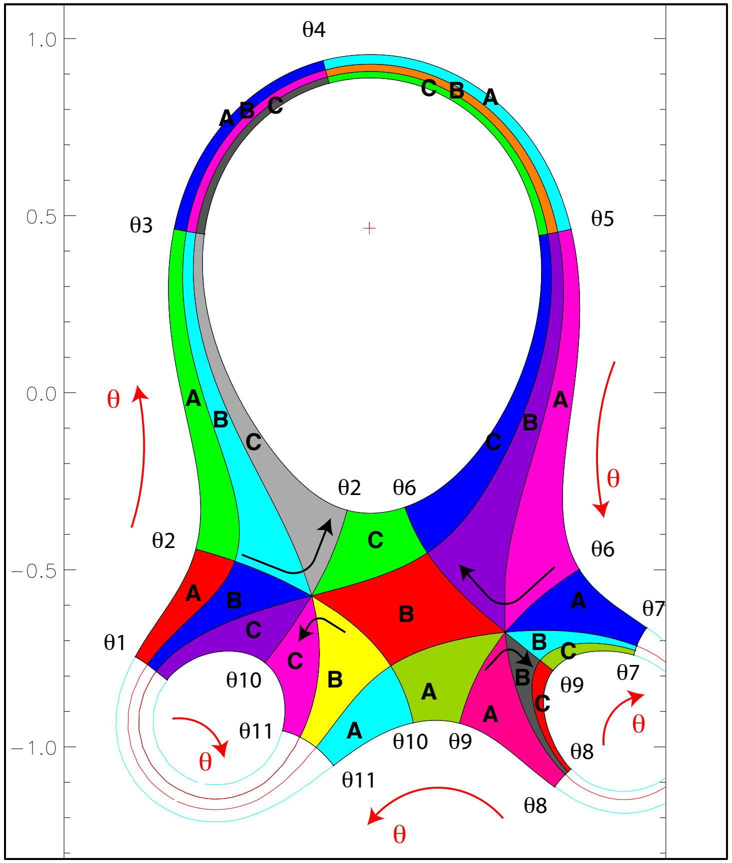


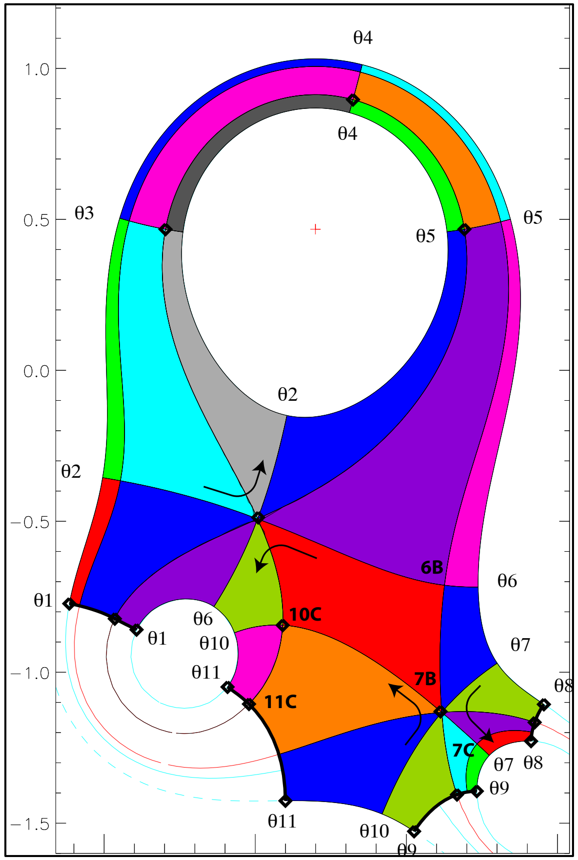



# From the point of view of domain topology and grid connectivity there are two distinct SFM regimes

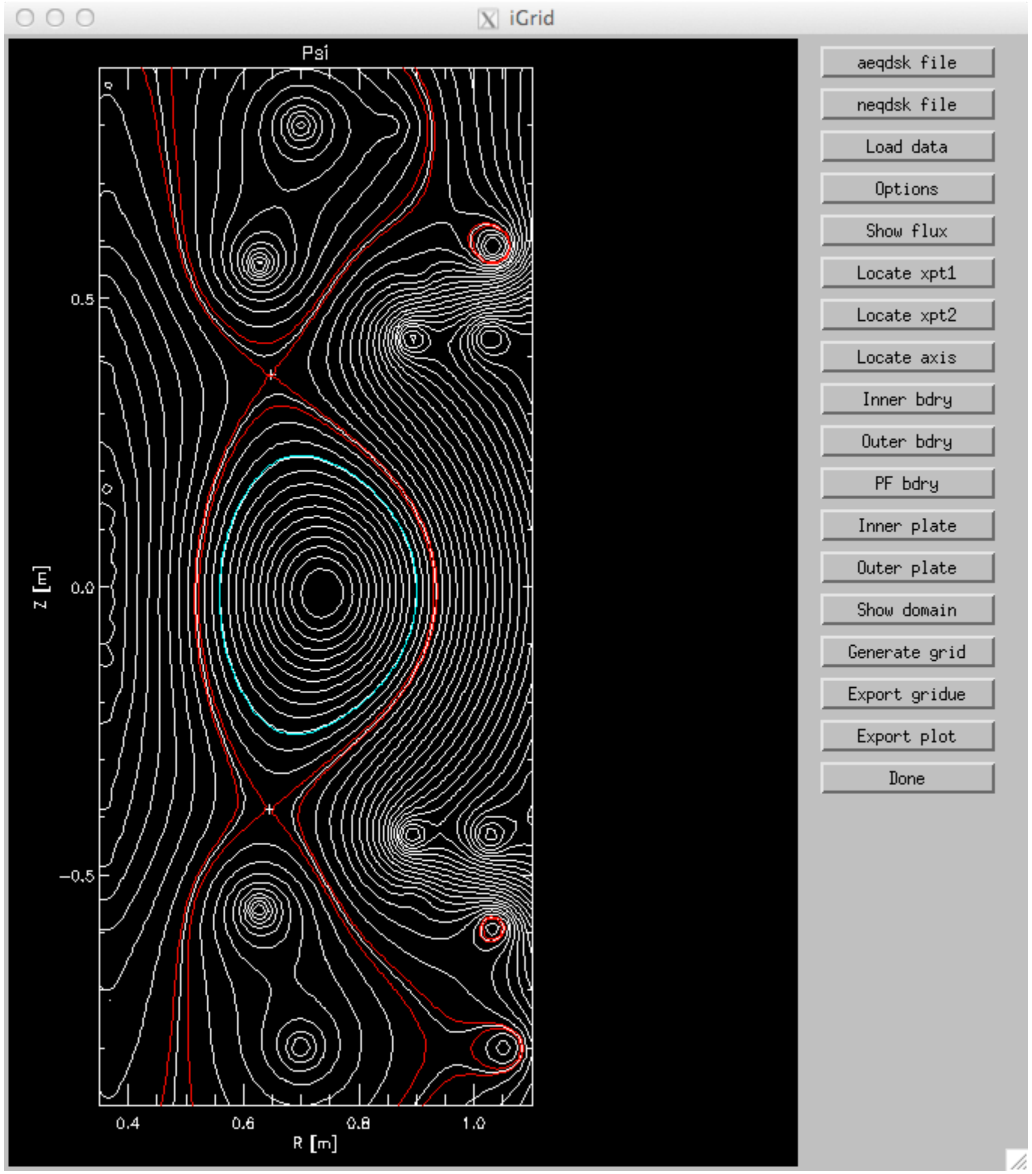
**SFM1 – From core boundary there is a path down grad(ψ) to PF boundary**

**SFM2 – From core boundary down grad(ψ) can only get to SOL boundary**



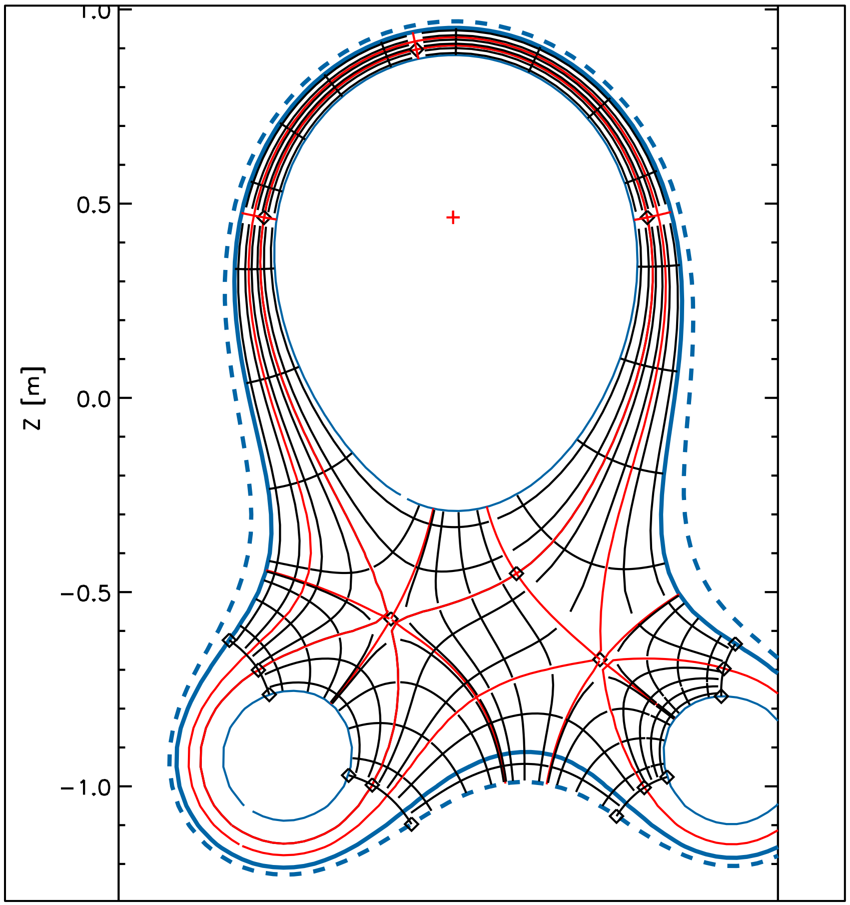
# Interactive Grid Generator iGrid (under continuing development) has been used for constructing meshes



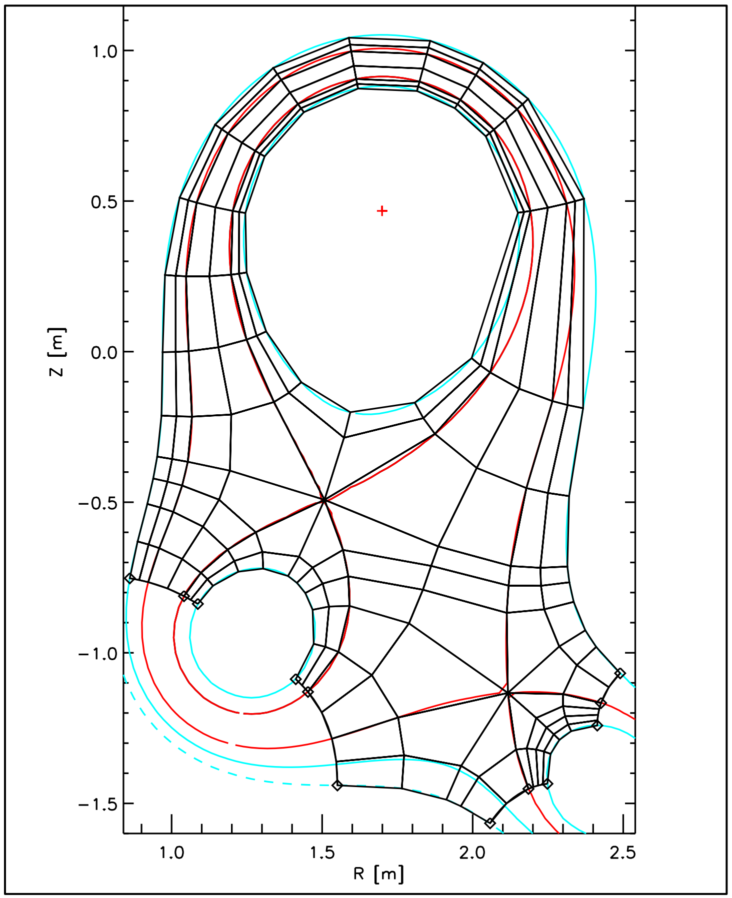

- Variety of flux surface geometry is a challenge for tokamak edge grid generation
- Human eye is still the best tool for recognizing complex patterns
- In iGrid the user guides the code by indicating with the mouse some needed reference points and directions

# Orthogonal grids for SFM1 and SFM2 are generated for analytic “3-wire” geometry

**SFM1 – From core boundary there is a path down grad(ψ) to PF boundary**

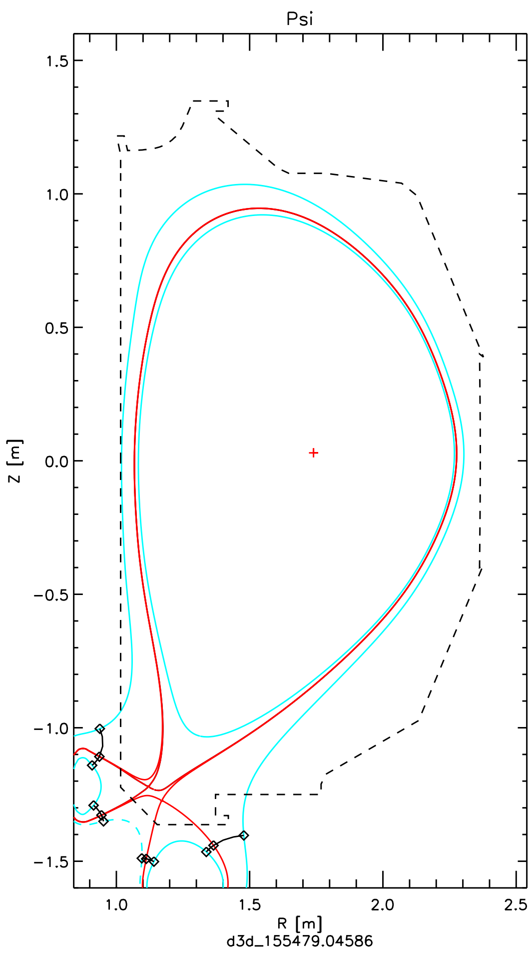



**SFM2 – From core boundary down grad(ψ) can only get to SOL boundary**

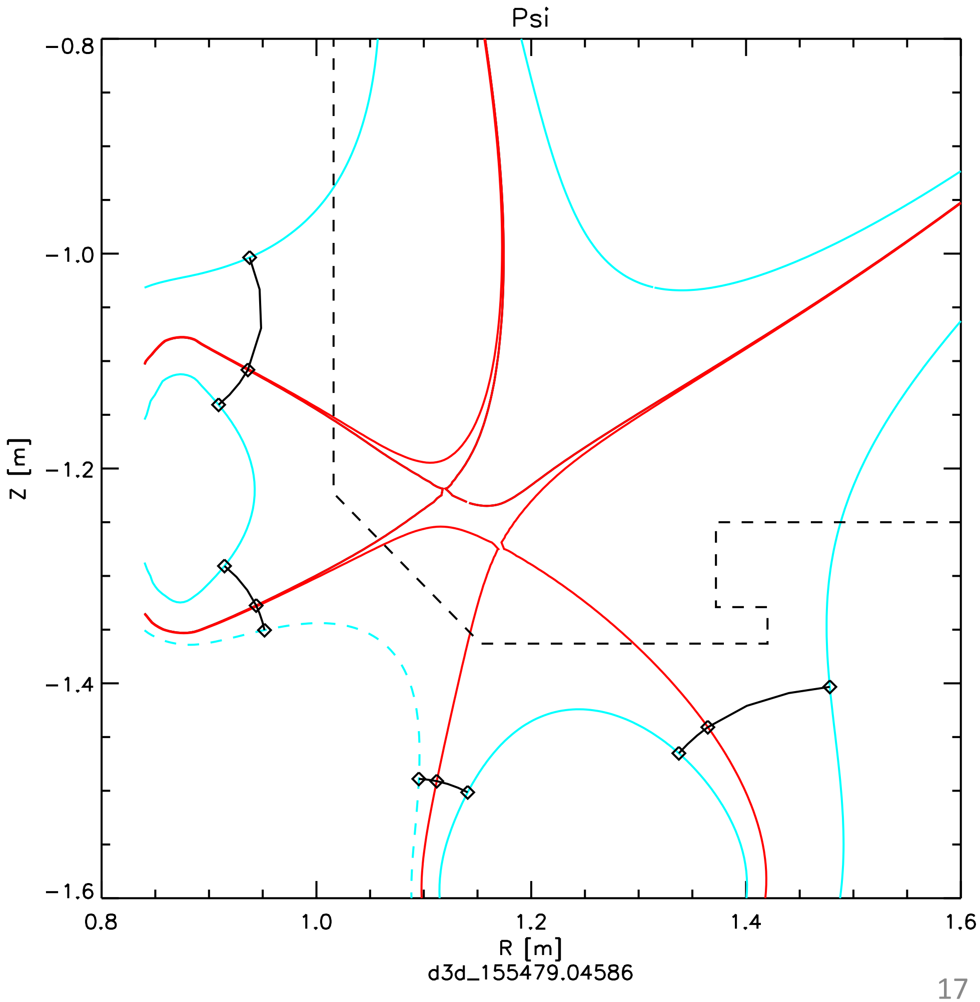


# Real tokamak geometry in near-snowflake configuration makes a challenge for grid numerics

**Actual DIII-D geometry**




**Extremely fast convergence of flux surfaces**



# Outline

- Divertor configurations with secondary X-points
- Snowflake divertor experiments
- X-Point target divertor
- Topology and grids for edge domain with two x-points
- **UEDGE analysis of near-snowflake divertor configurations**
- UEDGE analysis of X-point target divertor configuration
- Summary/Conclusions

# UEDGE* (Unified EDGE code) solves a system of fluid equations in axisymmetric tokamak geometry

**plasma density**

$$\frac{\partial}{\partial t}(n_i) + \nabla \bullet (n_i \vec{u}_i) = -S_r + S_i$$

$$n_i u_\perp = -D_{\perp i} \nabla_\perp n_i$$

**ion II momentum**

$$\frac{\partial}{\partial t}(m n_i u_{\parallel i}) + \nabla \bullet (m n_i u_{\parallel i} \vec{u}_i - \eta_i \nabla u_{\parallel i}) = -\nabla_\parallel P_i + m n_N n_i K_{cx}(u_{\parallel N} - u_{\parallel i}) + m S_r u_{\parallel N} - m S_i u_{\parallel N}$$

**electron thermal energy**

$$\frac{\partial}{\partial t}(3/2 n_e T_e) + \nabla \bullet (\frac{5}{2} n_e T_e \vec{u}_e + \vec{q}_e) = \vec{u}_e \bullet \nabla(3/2 n_e T_e) - \Pi_e \bullet \nabla \vec{u}_e + Q_e$$

**ion thermal energy**

$$\frac{\partial}{\partial t}(3/2 n_i T_i) + \nabla \bullet (\frac{5}{2} n_i T_i \vec{u}_i + \vec{q}_i) = \vec{u}_i \bullet \nabla(3/2 n_i T_i) - \Pi_i \bullet \nabla \vec{u}_i + Q_i$$

**ad-hoc radial transport**

$$q_\perp = -n\, \chi_\perp \nabla_\perp T$$

**neutral density**

$$\frac{\partial}{\partial t}(n_N) + \nabla \bullet (n_N \vec{u}_N) = S_r - S_i$$

$$n_N u_{\perp N} = -D_{\perp N} \nabla_\perp n_N$$

**neutral II momentum**

$$\frac{\partial}{\partial t}(m n_N u_{\parallel N}) + \nabla \bullet (m n_N u_{\parallel N} \vec{u}_N - \eta_N \nabla u_{\parallel N}) = -\nabla_\parallel P_N - m n_N n_i K_{cx}(u_{\parallel N} - u_{\parallel i}) - m S_r u_{\parallel N} + m S_i u_{\parallel N}$$

**charge conservation**

$$\nabla \bullet J(\phi) = 0$$

$$J_\parallel = \frac{en}{0.51 m\nu} \frac{B_x}{B} \left( \frac{1}{n}\frac{\partial P_e}{\partial x} - e\frac{\partial \phi}{\partial x} + 0.71 \frac{\partial T_e}{\partial x} \right)$$

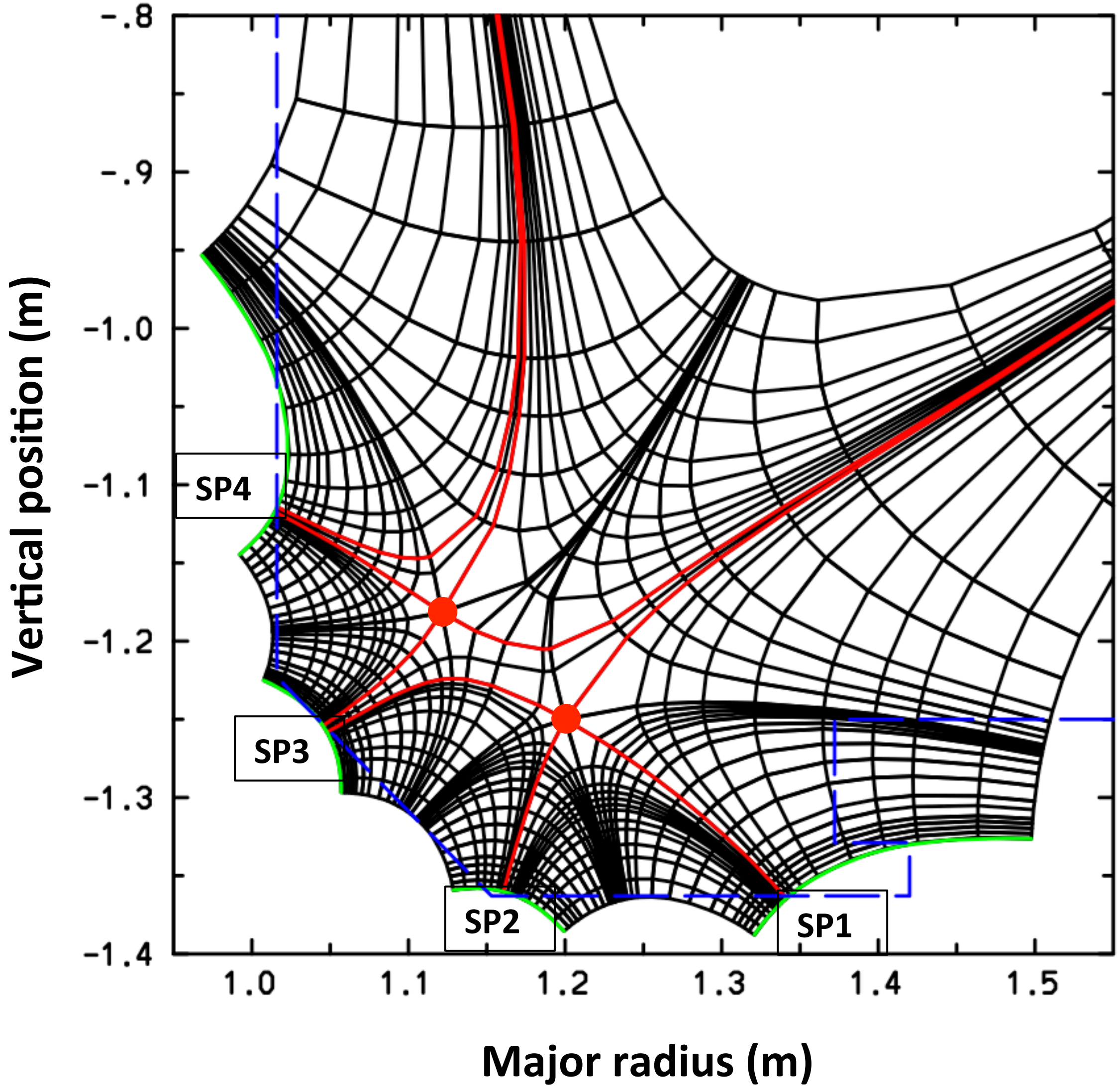
$$J_r = \sigma_\perp E_r$$

**sheath bound. cond.**

$$\phi = \frac{-Te}{e} \ln\left[ 2\sqrt{\pi} \left( \frac{J_\parallel - enu_{\parallel i}}{env_{te}} \right) \right]$$

*T. D. Rognlien et al., J. Nucl. Mater. 196–198, 347 (1992)

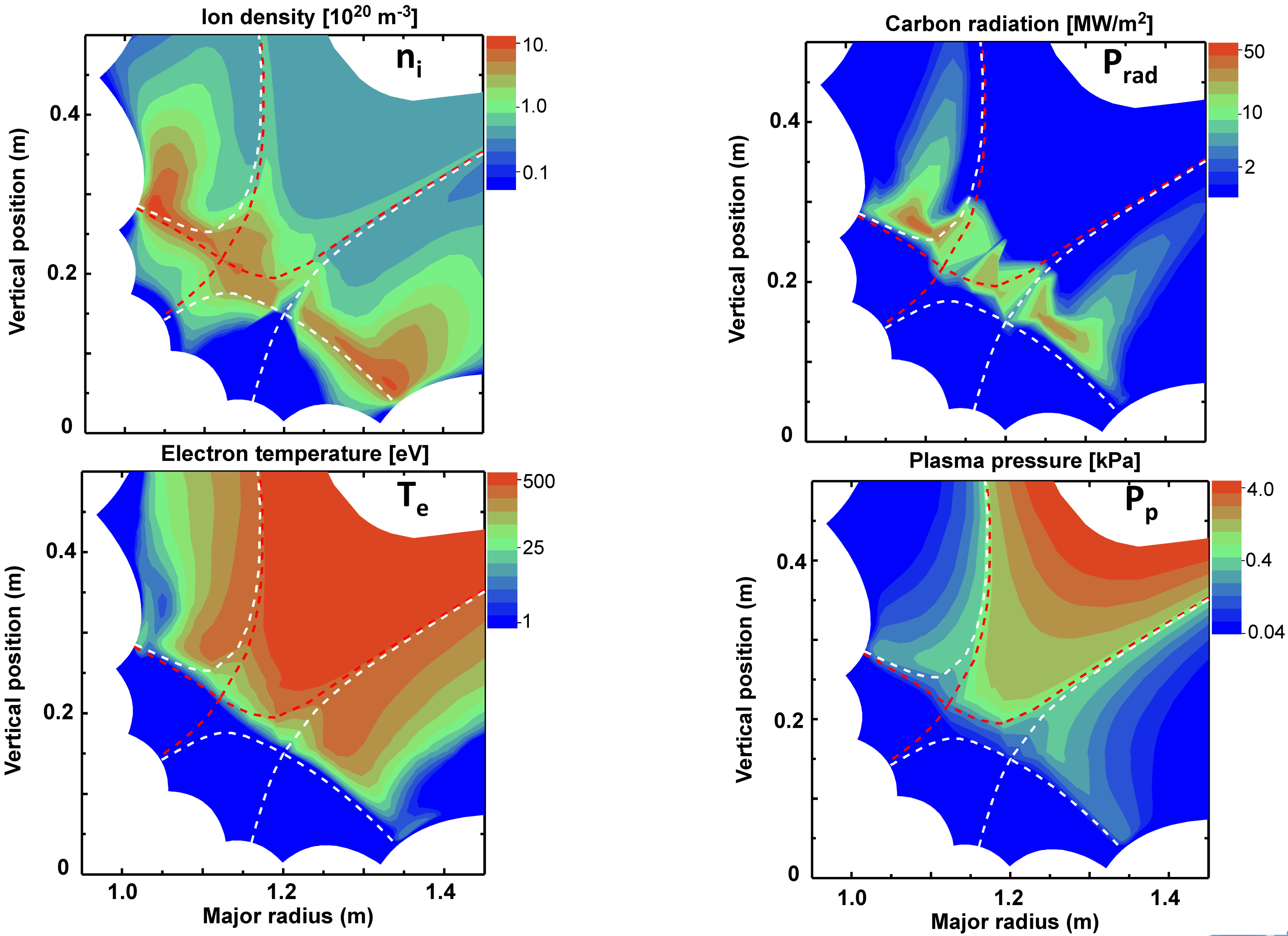
# UEDGE SFM1 mesh for DIII-D shot 155479



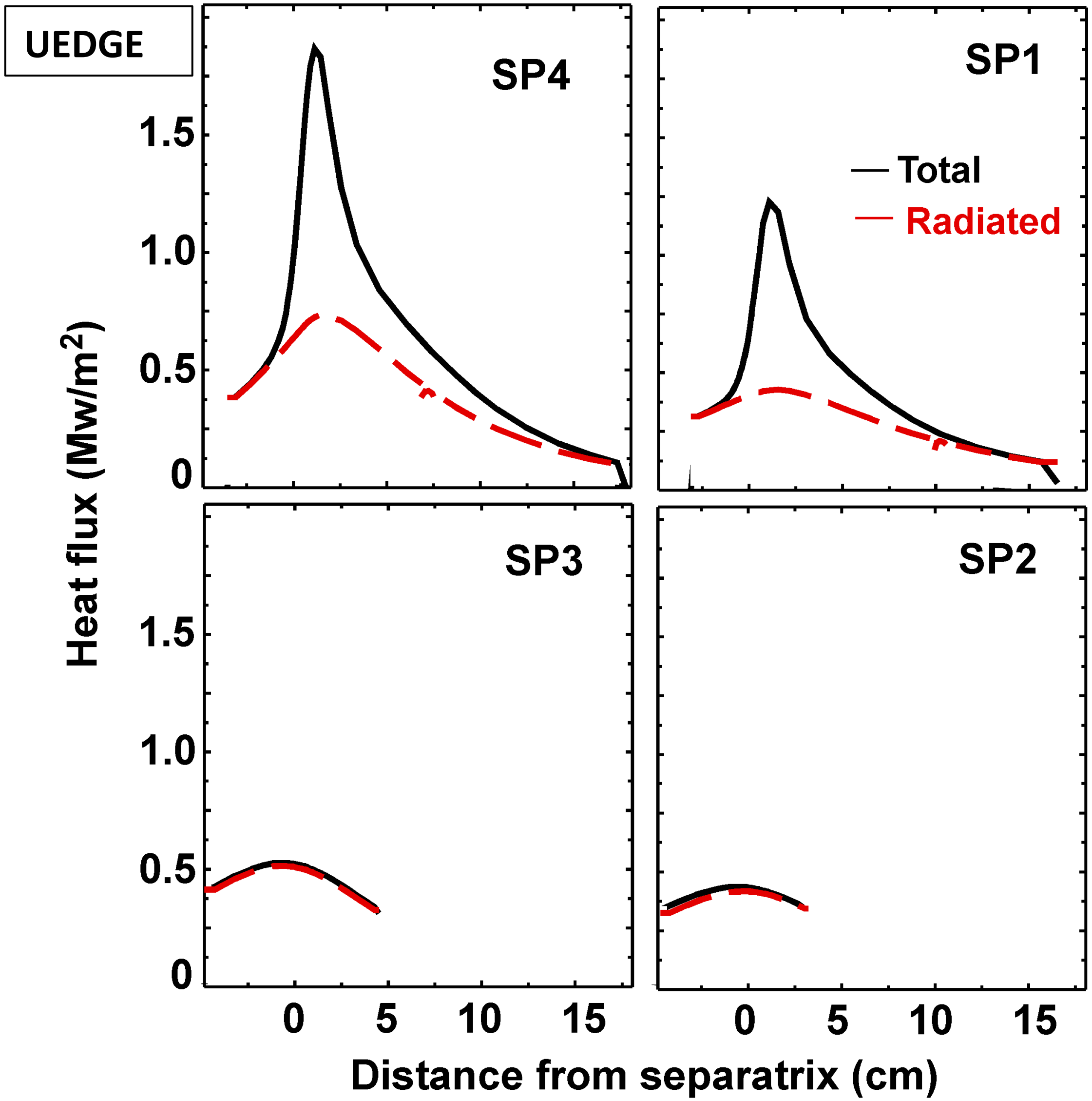

**X-point separation/ minor radius**
**σ = 0.1/0.5 = 0.2**

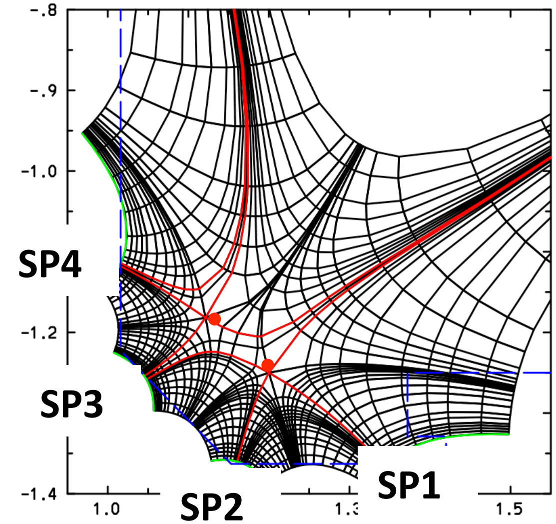
**50% greater mesh resolution used for simulations**

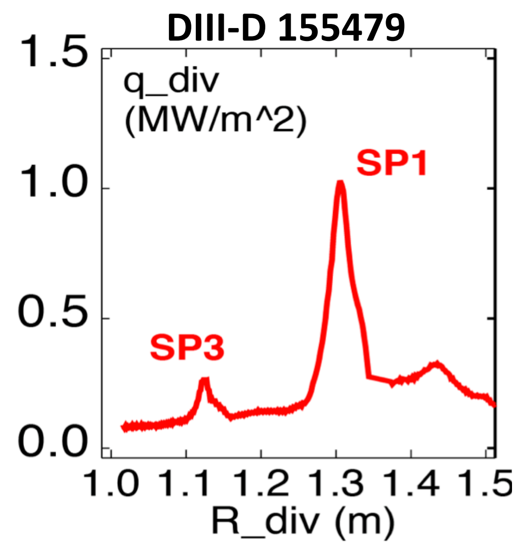
# 2D UEDGE SF solutions for 2% carbon show strong variations across separatrices; radiation is well spread



# Plate heat-fluxes are < 2 MW/m$^2$; only radiative flux is visible in the middle between two strike points (2% carbon)



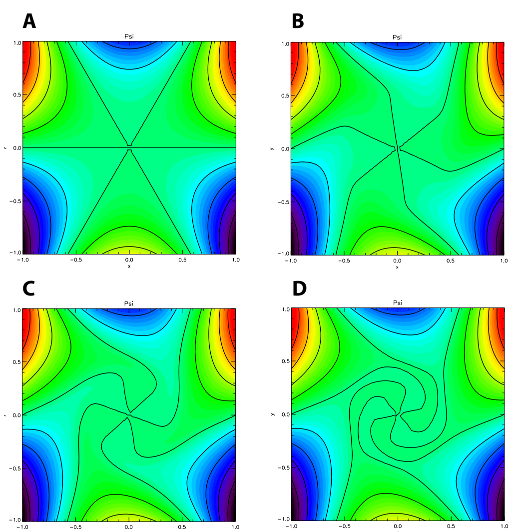




Distance across plate [m]

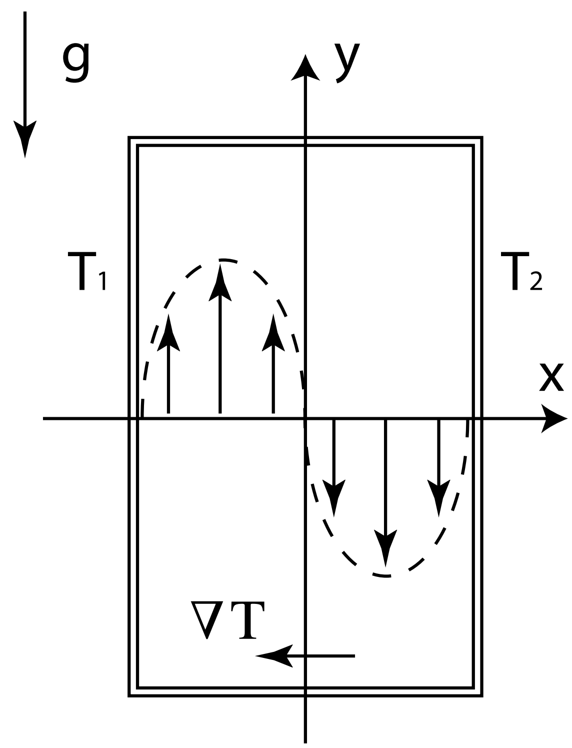
# Convective cell formation near null dubbed "the churning mode" may be responsible for heat redistribution*

**Driven by crossed magnetic curvature and grad(P) near null where poloidal beta is large**

**Solving plasma fluid equations demonstrates formation of the churning mode****




**Similar to thermal convection due to crossed gravity and temperature gradient**

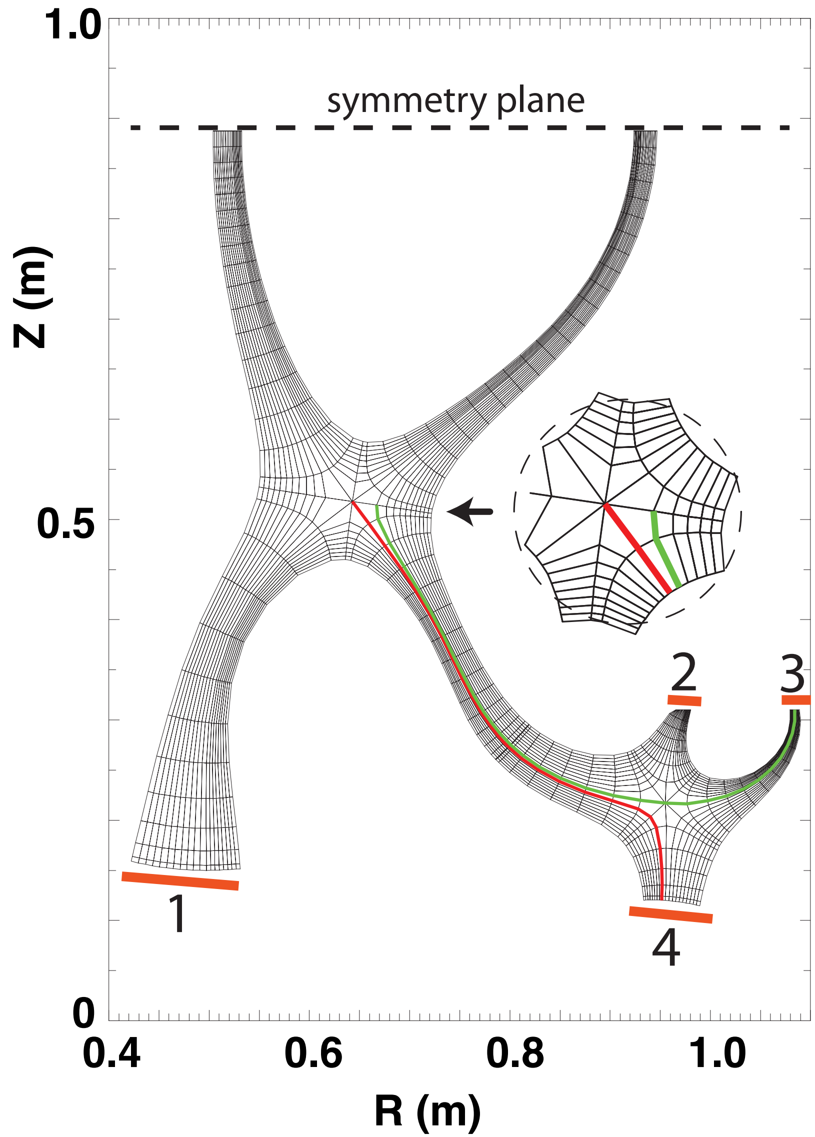



*D.D. Ryutov et al., Physica Scripta 89, 8, 088002 (2014)
** M.V. Umansky and D.D. Ryutov, submitted (2015)

# Outline

- Divertor configurations with secondary X-points
- Snowflake divertor experiments
- X-Point target divertor
- Topology and grids for edge domain with two x-points
- UEDGE analysis of near-snowflake divertor configurations
- **UEDGE analysis of X-point target divertor configuration**
- Summary/Conclusions

# UEDGE is used to model both X-points in an XPTD for the lower half of up-down symmetric configuration




**Mesh constructed in UEDGE by combining two lower-half single-null domains (with scripts developed by M.E. Rensink)**

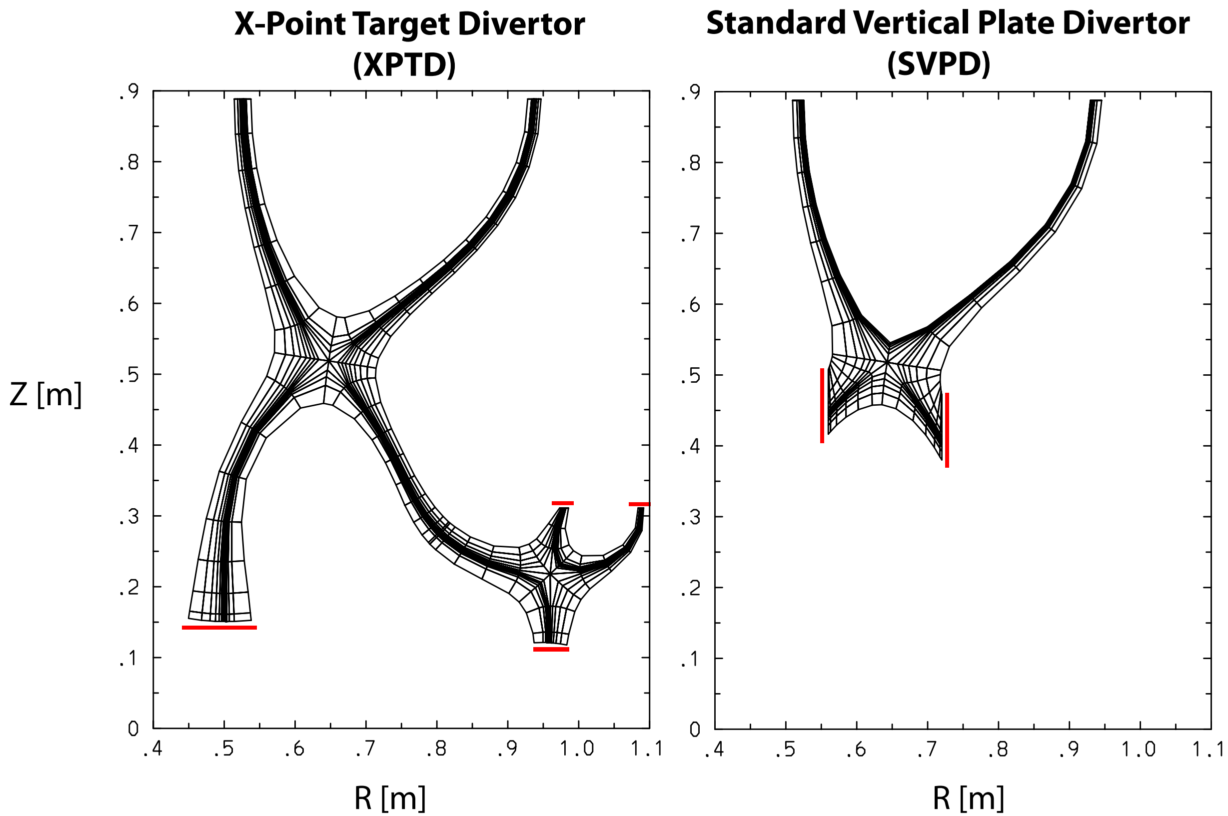
**<u>Use UEDGE fluid transport model</u>**

- **Fluid neutrals (inertial)**
- **Fixed fraction impurity radiation**
- **No drifts**
- **Four orthogonal target plates**
- **100% recycling on all walls**

**<u>Use geometry & parameters from LaBombard et al., NF 2015</u>**

- **MHD equilibrium provided by MIT**
- **Density at separatrix ~ 1e20 $m^{-3}$**
- **Power into lower-half domain 1-5 MW**

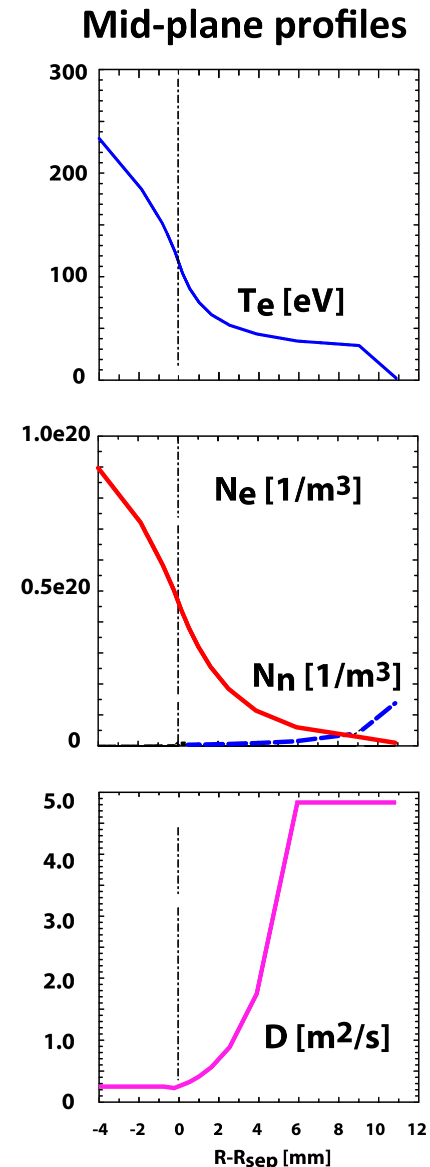
# A C-Mod like case with ADX parameters is used for comparison




- **Two configurations – XPTD and SVPD**
- **Same underlying magnetic geometry, physics model, boundary conditions, etc.**
- **In SVPD the legs cut short to roughly match C-Mod vertical plate configuration**

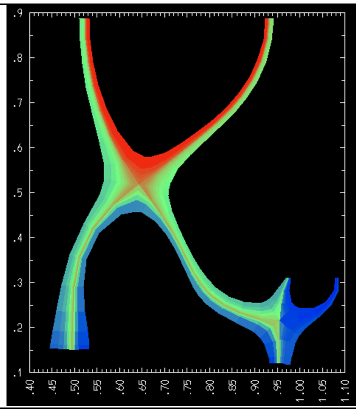
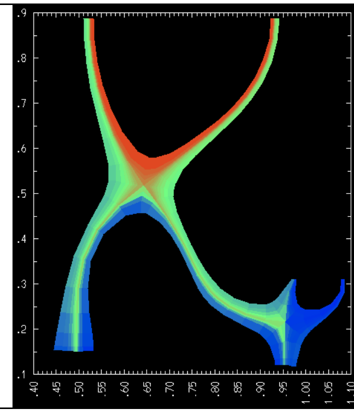
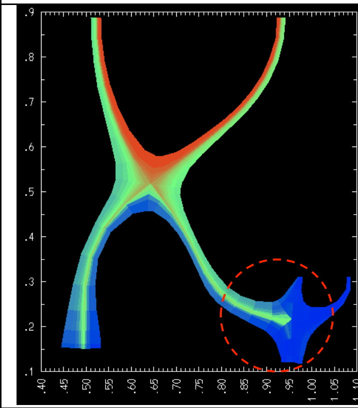
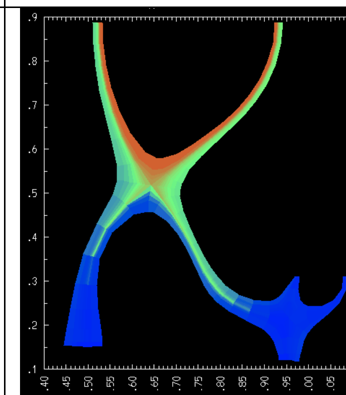
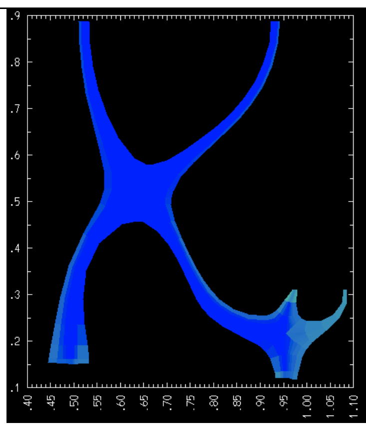
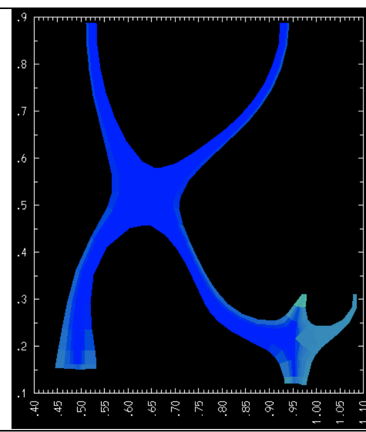
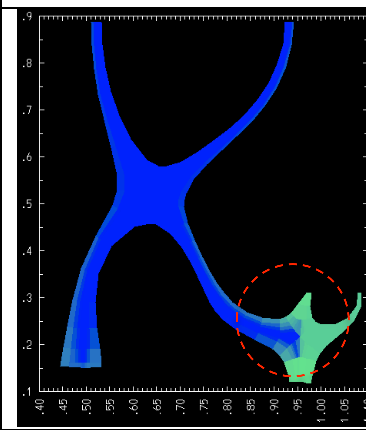
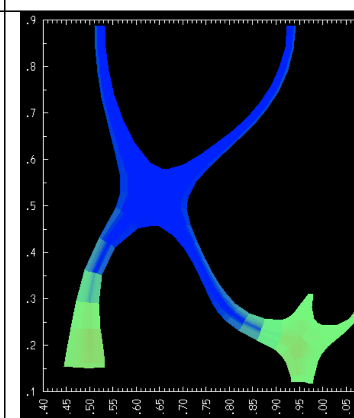
# Radial transport parameters are set to match projected ADX upstream SOL characteristics

- **Using fully recycling wall B.C. on all material surfaces**
- **Using radially growing diffusing coefficient to match the expected density profile width ~5 mm**
- **Spatially constant $\chi_{e,i}$ is sufficient to achieve ~3 mm width of mid-plane $T_{e,I}$**
- **Mid-plane profile projections are based on C-Mod data***



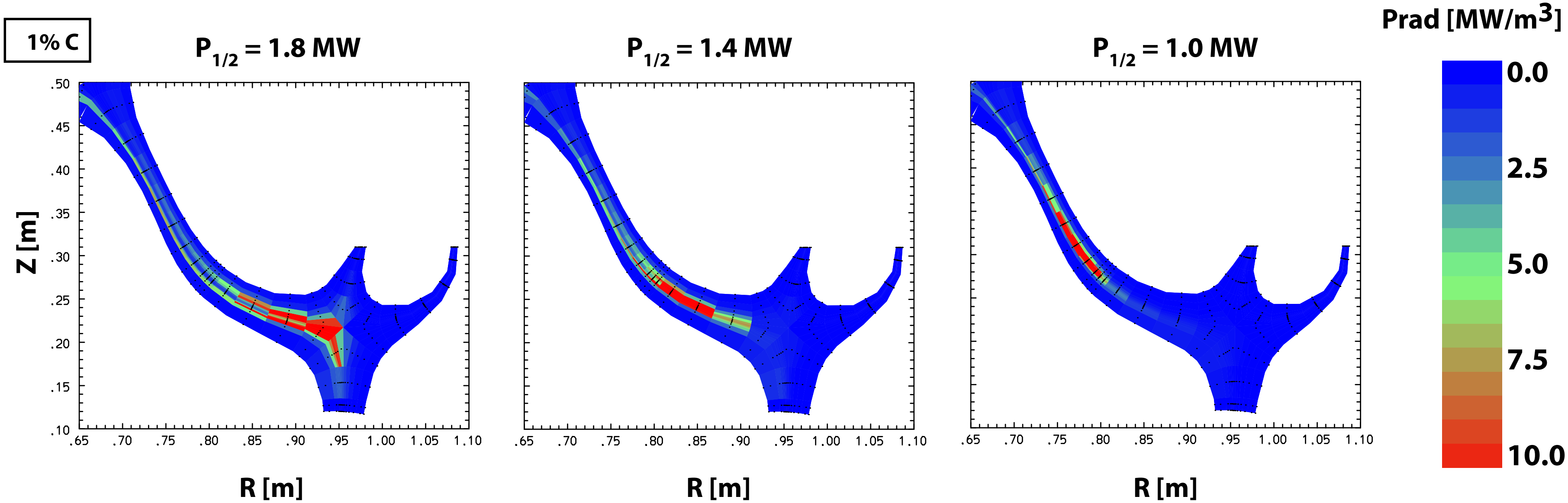

***LaBombard et al., Nucl. Fusion 55, 053020, 2015.**

# As the input power $P_{1/2}$ is reduced, the divertor transitions to fully detached state

| | A | B | C | D |
|---|---|---|---|---|
| | $P_{1/2}$=3.000 MW | $P_{1/2}$=2.058 MW | $P_{1/2}$=2.052 MW | $P_{1/2}$=1.420 MW |
| lg(Te [eV]) | | | | |
| 0.00<br>0.75<br>1.50<br>2.25<br>3.00 |  |  |  |  |
| lg(Ng [m-3]) | | | | |
| 18<br>19<br>20<br>21<br>22 |  |  |  |  |

XPTD, 1% C

# As input power $P_{1/2}$ is reduced, radiation front remains stable but shifts upstream



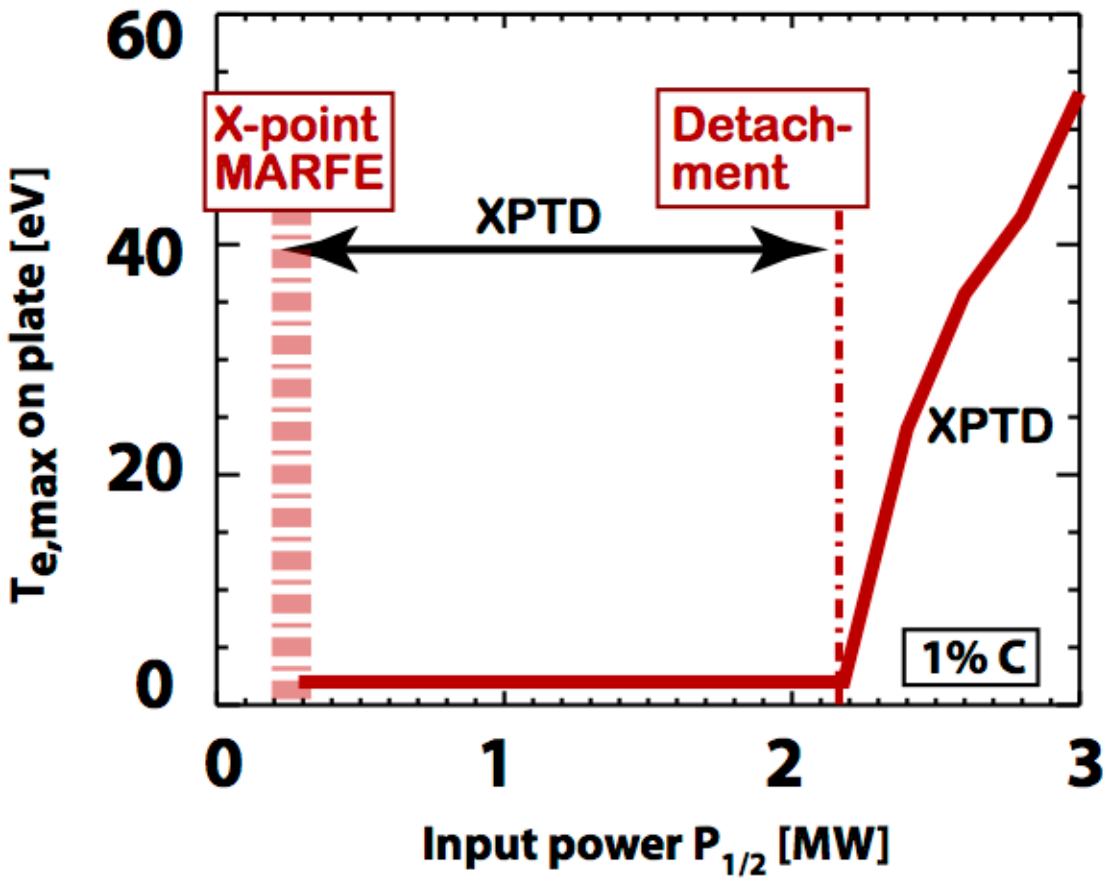

- **For higher input power the radiation front moves to larger R to increase the radiating volume***

- **$P_{1/2}$ ≈ 2 MW onset of detachment**

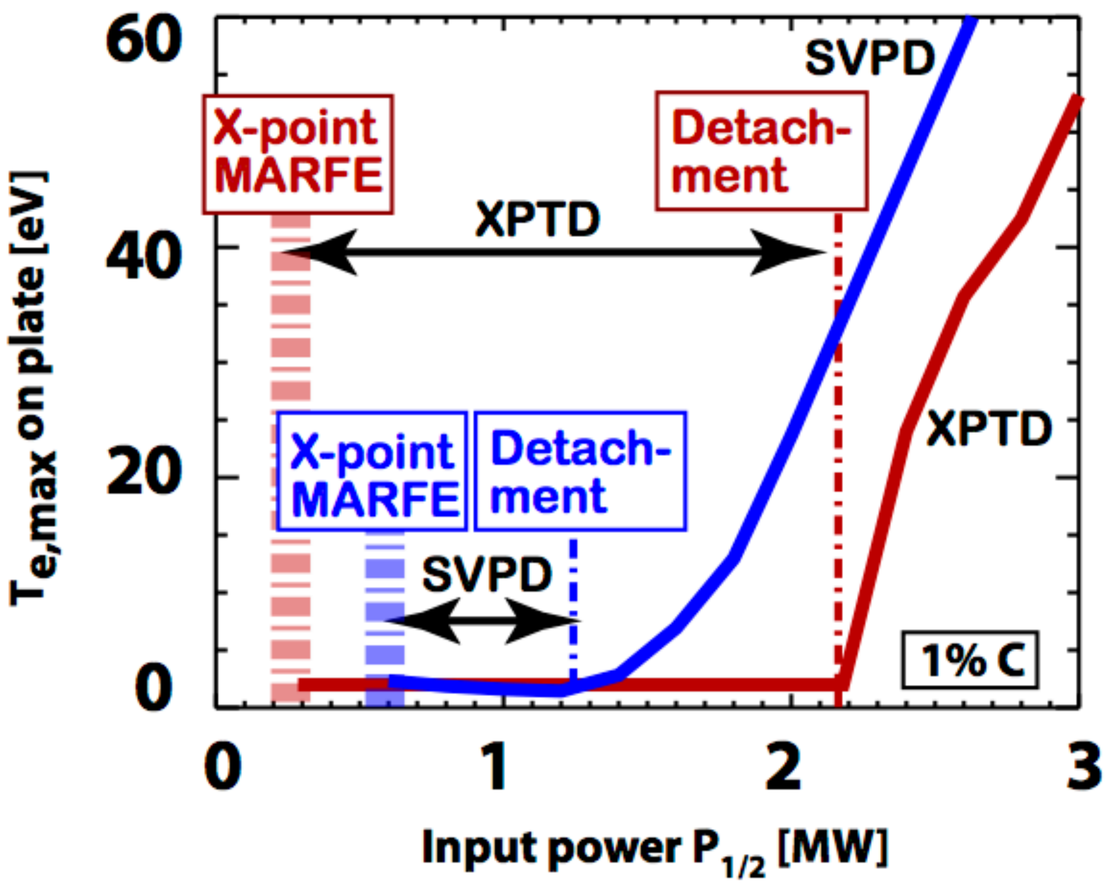
- **As $P_{1/2}$ is reduced further either (i) the radiation front reaches the primary X-point, or (ii) no steady-state solutions can be found => X-point MARFE**

***Hutchinson, Nucl. Fusion 34 (1994) 1337**

# Reducing input power $P_{1/2}$ eventually leads to X-point MARFE



# Reducing input power $P_{1/2}$ eventually leads to X-point MARFE




- Qualitatively similar results also obtained with 1% Ne impurity

# Outline

- Divertor configurations with secondary X-points
- Snowflake divertor experiments
- X-Point target divertor
- Topology and grids for edge domain with two x-points
- UEDGE analysis of near-snowflake divertor configurations
- UEDGE analysis of X-point target divertor configuration
- **Summary/Conclusions**

# Summary, conclusions, plans

- **Capability to generate grids with a secondary X-point is developed**
- **Capability to model configurations with a secondary X-point is developed in UEDGE**
- **Near-SNF configurations in DIII-D have been analyzed with UEDGE; points to strongly enhanced transport near the null (churning mode?)**
- **X-point Target Divertor (XPTD) configuration is studied with UEDGE for parameters matching the design of ADX tokamak**
  - **Steady state detachment found for XPTD, for a range of parameters**
  - **Easier to achieve detachment than for short leg divertor**
  - **Detachment front stays far away from the main X-point**
  - **Stable fully detached regimes for tokamak divertor?**